Modeling Sediment Transport in Energetic Wave Bottom Boundary Layers

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LONG-TERM GOALS

The goals of this work are to develop a better understanding of the sediment transport in <u>wave</u> <u>bottom-boundary layers</u> (WBBL) in the nearshore and inner shelf and to develop predictive capabilities for their effects as a function of important environmental parameters, such as wave heights, sediment properties, beach slope, local water depth, wave frequency spectra, and the presence of mean currents.

OBJECTIVES

The major tasks are to:

(1) develop a 3-D model for sediment transport that treats sandy sea beds as a mixture having variable density and viscosity that depend on the local sediment concentration

(2) complete sets of direct numerical simulations of sediment transport under oscillatory flow conditions

(3) determine the effect of environmental parameters and physical properties on flow dynamics

(4) compare vertically-averaged 3-D results with field and laboratory data

APPROACH

We are extending the current theory and numerical modeling capabilities for the WBBL to include the case of sediment transport over a sandy sea bed for sheet flow conditions in the nearshore and inner shelf regions. We have chosen to use an approach that assumes a system containing sediment particles can be approximated as a mixture having variable density and viscosity that depend on the local sediment concentration. Fluid-particle and particle-particle interactions are expressed through the mixture viscosity and a stress-induced diffusion term for sediment motion. The work involves theoretical development, numerical computations, and comparisons with field and laboratory data.

In this approach, there are five governing equations that describe the flow field,

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_j}{\partial x_j} = 0 \tag{1}$$

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14. ABSTRACT

The goals of this work are to develop a better understanding of the sediment transport in wave bottom-boundary layers (WBBL) in the nearshore and inner shelf and to develop predictive capabilities for their effects as a function of important environmental parameters, such as wave heights, sediment properties, beach slope, local water depth, wave frequency spectra, and the presence of mean currents.

15. SUBJECT TERMS

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$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial \rho u_i u_j}{\partial x_j} = -\frac{\partial P}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + F\delta_{i1} - \rho g \delta_{i3} \qquad \text{2)}$$

$$\frac{\partial C}{\partial t} + \frac{\partial C u_j}{\partial x_j} = -\frac{\partial C W_t}{\partial z} + \frac{\partial N_j}{\partial x_j} \qquad \text{3)}$$

where Eqs. (1) and (2) are the mixture continuity and momentum equations, Eq. (3) is the species continuity equation for the sediment, ρ is the mixture density, u is the mixture velocity, P is pressure, τ is the stress tensor, F is the external driving force, g is the gravitational constant, C is the sediment volume concentration, W_t is the settling velocity, and N is the "diffusive" flux of sediment. The mixture density and viscosity are calculated using $\rho = (1-C)\rho_f + C\rho_s$ and $\mu = \mu_f \left[1 + \frac{1.5 C C_p}{C_p - C}\right]^2$,

where ρ_f and ρ_s are the fluid and sediment densities, μ_f is the fluid viscosity, and C_p is the maximum packing concentration of sediment (e.g., $C_p = 0.64$ for random close packing). Fluid-sediment mixtures have been shown to behave as Newtonian fluids and the stress tensor is given by

$\tau_{ij} = \mu \left[\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\frac{\partial u_k}{\partial x_k}\right]$. Richardson and Zaki (1954) showed that $W_t = W_{t0}(1-C)^q$ can be used

to calculate settling velocity as a function of sediment concentration, where W_{t0} is the settling velocity

of a single particle in a clear fluid and q is an empirical constant that depends on the particle Reynolds

number $\left(\text{Re}_p = \frac{d\rho_f |W_{t0}|}{\mu_f}\right)$. Sediment diffusion can depend on the collision frequency, the spatial

variation of viscosity, and Brownian diffusion, such that $N = N_c + N_\mu + N_B$, where N_c is the flux due

to collisions, N_μ is the flux due to viscosity variation, and N_B is the flux due to Brownian diffusion.

The expression for sediment diffusion developed by Nir and Acrivos (1990) for sediment flow on

inclined surfaces is used as a first approximation. Their expression accounts for the flux due to

collisions only and follows a Fickian diffusion form with a variable diffusion coefficient that is a

function of particle size, concentration, and mixture stresses so that $N_j = D_j \frac{\partial C}{\partial x_j}$, where

$$D_j = d^2 \frac{1}{3} C^2 \left(1 + \frac{1}{2}e^{8.8C}\right) \left|\frac{\partial u_i}{\partial x_j}\right|.$$

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WORK COMPLETED

During this phase of the project our focus has been on model development, coding, testing and debugging. The model has been coded and debugged and is in the testing stage. Direct numerical simulations of sediment transport under oscillatory flow conditions are being carried out to determine the effect of environmental parameters and physical properties of the flow dynamics and comparison with field and laboratory data is under way to determine model validity.

RESULTS

The turbulent dynamics of an initially stationary densely packed sand layer (60% by volume sand), driven by a sinusoidally oscillating flow, are examined and model results are compared with the experimental data of Horikawa, Watanabe, & Katori (1982). Figure 1 compares experimental and model sheet flow layer thickness as a function of phase, θ, where we define the sheet flow layer as the layer where $0.05 \leq C \leq 0.95$. The figure shows the model predictions are within a factor of 6 of the experimental data for all phases. The experimental data and model prediction matches exactly when the velocity is at a maximum ($\theta = 90°$) and are within a factor of 1.4 when the velocity changes direction ($\theta = 0°$). Figure 2 compares the experimental data and model vertical concentration profiles as a function of phase. The figure shows that the model profiles have similar shapes to the experimental profiles and fall reasonably close to the experimental data. Overall, the model does the best job of predicting sheet flow layer thickness and vertical concentration profile when the velocity reaches a maximum and when it changes direction. Figure 3 shows 3-D concentration profiles as a function of phase. A significant amount of sand is entrained during the acceleration phase ($\theta = 0°$ - 90°) of the wave cycle, which then falls back during the deceleration phase ($\theta = 90°$ - 180°) of the cycle.
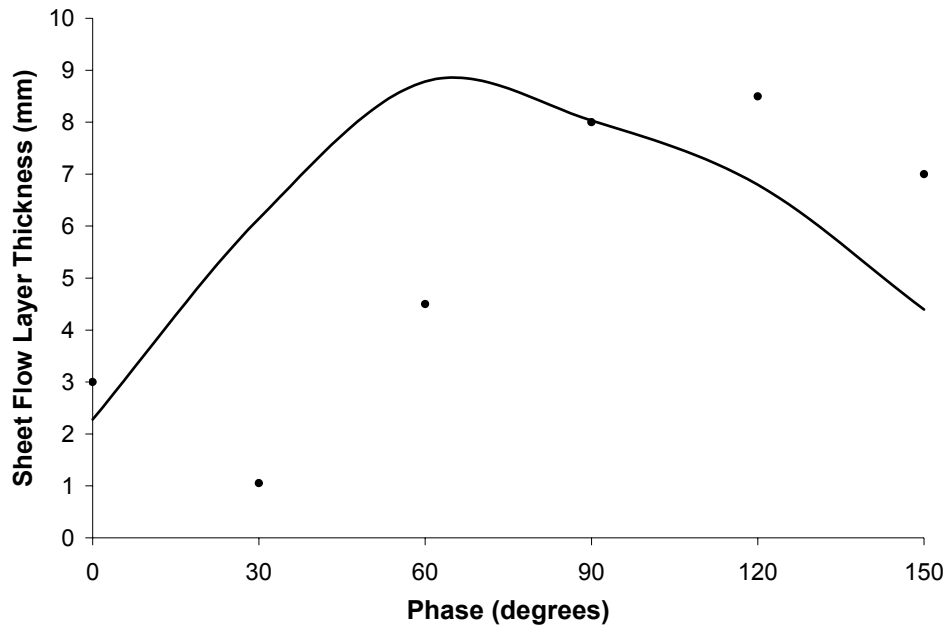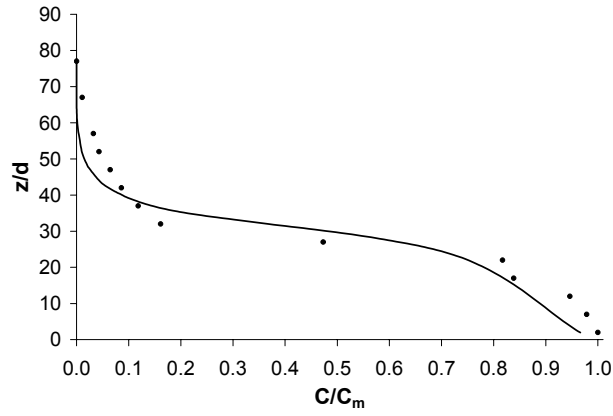

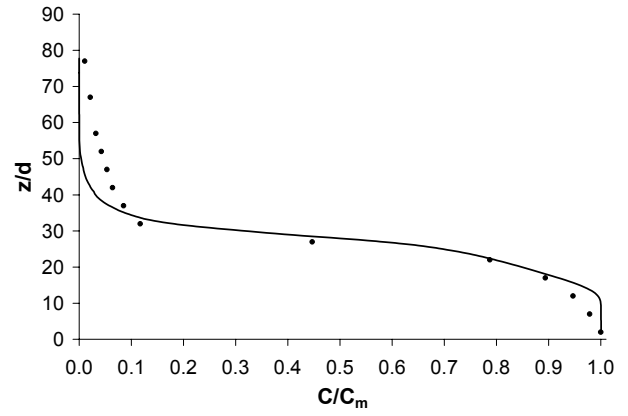*Figure 1. Sheet flow layer thickness as a function of phase.*
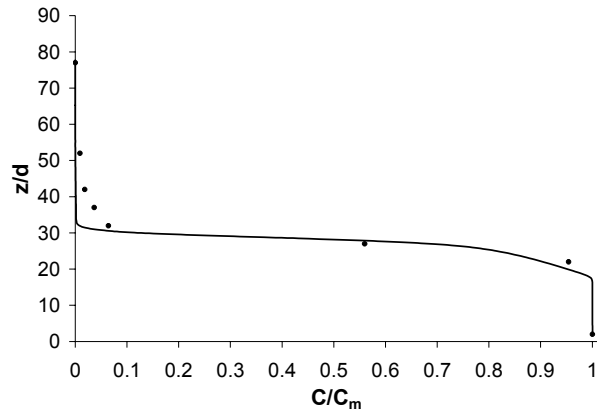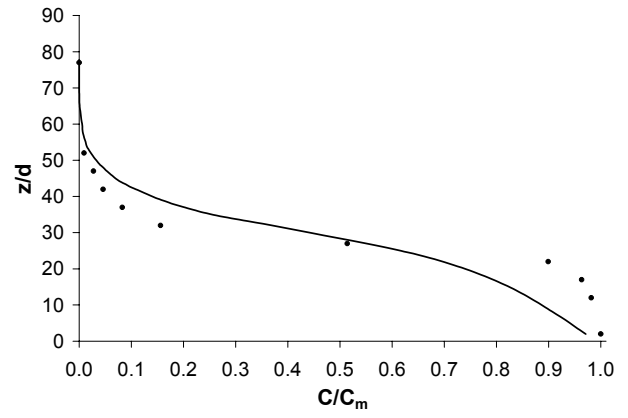
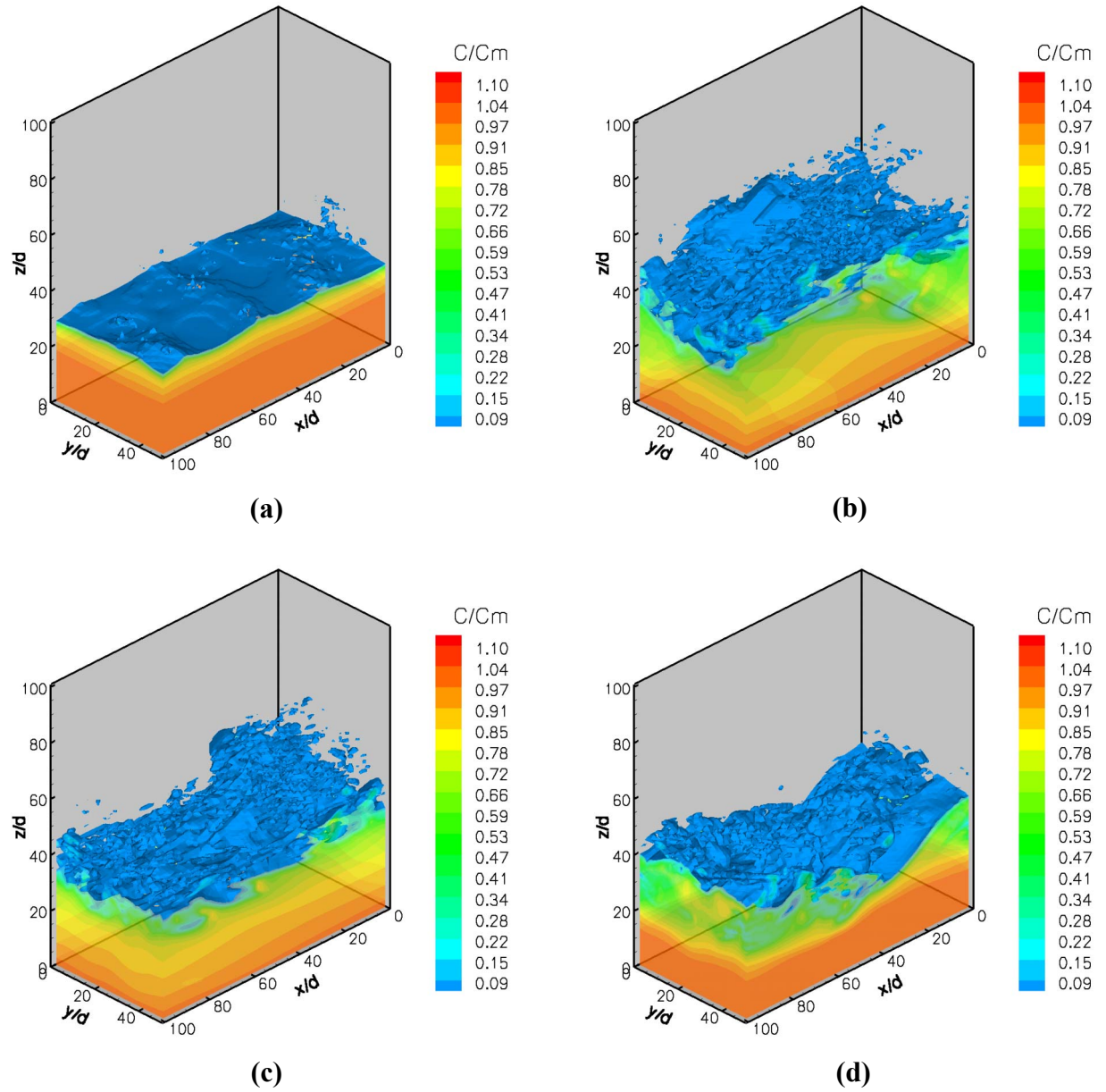***Figure 2. Vertical concentration profiles, (a) $\theta = 0°$, (b) $\theta = 60°$, (c) $\theta = 90°$, and (d) $\theta = 150°$;***
● Horikawa, Watanabe, & Katori data, ——model; $C_m = 0.6 \ cm^3 \ sand/cm^3$; $d = 0.02 \ cm$.

Figure 3. 3-D concentration profiles, (a) $\theta = 0°$, (b) $\theta = 60°$, (c) $\theta = 90°$, and (d) $\theta = 150°$; $C_m = 0.6 \ cm^3 \ sand/cm^3$; $d = 0.02 \ cm$.

IMPACT/APPLICATIONS

Improved understanding of the near shore environment has potential benefits for society in several areas. These include shore protection against beach erosion; understanding the behavior of shoaling waves; keeping waterways open for shipping in harbors, ports and inlets; safety for recreational beach users (e.g., from dangerous rip currents); and in defense of the nation when activities encompass littoral regions. We will have a strong indication that we understand and can quantify important

nearshore processes when predictive models can match field observations. For the scientific community, this is still a work in progress.

TRANSITIONS

Our major transition has been in understanding how sediment entrainment can be described using a shear-induced diffusion term.

RELATED PROJECTS

1. ONR is supporting the SAX04-Sand Ripple Departmental Research Initiative to learn more about the development of sand ripples and their impact on acoustic propagation into the sea-bed.

2. A group of near shore researchers, led by Jim Kirby at the University of Delaware, focusing on nearshore processes and sediment transport properties, are developing related near shore community models under a NOPP project.

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